

Photometric Study of Variable Stars in the Open Cluster NGC 6866

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e-mail: (molenda,kopacki)@astro.uni.wroc.pl*Received Month Day, Year***ABSTRACT**

We report the discovery of 19 variable stars and two blue-stragglers in the field of the open cluster NGC 6866. Three of the variable stars we classify as δ Sct, two, as γ Dor, four, as W UMa, two, as ellipsoidal variables, and one, as an eclipsing binary. Seven stars show irregular variability. Two of the pulsators, a δ Sct star NGC 6866-29 and a γ Dor star NGC 6866-21, are multiperiodic.

From an analysis of proper motions, we conclude that the δ Sct stars, one of the γ Dor stars and both blue-stragglers are very probable members of the cluster. The position on the color-magnitude diagram of seven other variables suggests that they also belong to the cluster. The eclipsing binary, which we discover to be a new high-velocity star, and the seven irregular variables are non-members.

Then, we discuss in detail the age and metallicity of open clusters that host γ Dor stars and we show that none of these parameters is correlated with the number of γ Dor stars in cluster.

Key words: *Stars: pulsating: δ Sct – Stars: pulsating: γ Dor – Stars: variable: other – Open clusters: individual: NGC 6866 – Space missions: Kepler*

1. Introduction

NGC 6866 ($\alpha_{2000} = 20^{\text{h}}03^{\text{m}}55^{\text{s}}$, $\delta_{2000} = 44^{\circ}09'30''$) is an intermediate-age open cluster classified as I 2p by Trumpler (1928) or II 2m by Ruprecht (1966). The cluster falls into the field of view of the Kepler satellite telescope which will observe selected stars from the Cygnus–Lyra region with the aim of searching for Earth-size planets and a detailed study of the structure of pulsating stars by means of the asteroseismic analysis (Christensen-Dalsgaard *et al.* 2006).

The first photometric study of the cluster dates back to the *UBV* photoelectric and photographic photometry of Hoag *et al.* (1961), Johnson *et al.* (1961), and Barkhatova & Zakharova (1970). Hoag *et al.* (1961) and Johnson *et al.* (1961) derived the distance modulus of the cluster, $V - M_V = 10.82$ mag, the color excess, $E(B - V) = 0.14$ mag, the distance, $d = 1200$ pc, and estimated the spectral type of the turn-off point to be A3. Subsequent observations of Sutantyo & Hidajat (1972) yielded $E(B - V) = 0.16$ mag and $V - M_V = 11.10$ mag. The catalogue

of astrophysical data for Galactic open clusters of Kharchenko *et al.* (2005) gives $E(B - V) = 0.17$ mag, $d = 1450$ pc, and $V - M_V = 11.33$ mag.

The estimates of the age of NGC 6866 range from 0.23 Gyr (Lindoff 1968) to 0.65 Gyr (Loktin *et al.* 1994) with the most recent determination, 0.48 Gyr, given by Kharchenko *et al.* (2005). The mean $[\text{Fe}/\text{H}]$ of the cluster has been derived by Loktin *et al.* (1994) from the photometry of Hoag *et al.* (1961) to be equal to $+0.10$ dex. The mean radial-velocity of the cluster has been measured by Mermilliod *et al.* (2008) and by Frinchaboy *et al.* (2008); these authors found the radial-velocity to be equal to 13.68 ± 0.06 and 12.18 ± 0.75 km/s, respectively. (Here, the uncertainty given by Mermilliod *et al.* (2008) is an r.m.s. error, while the uncertainty given by Frinchaboy *et al.* (2008), the standard deviation.)

The probability of the cluster membership has been computed by Baumgardt *et al.* (2000) for two stars, by Dias *et al.* (2002), for 89 stars, by Kharchenko *et al.* (2004), for 192 stars, and by Frinchaboy *et al.* (2008), for 52 stars (all in common with Dias *et al.* (2002)). Baumgardt *et al.* (2000) and Dias *et al.* (2002) based their computations on proper motions from the Tycho-2 catalogue (Høg *et al.* 2000). Kharchenko *et al.* (2004) used proper motions from the Tycho-2 catalogue, the available photometry and the stars' positions in the cluster. Frinchaboy *et al.* (2008) used radial velocities measured with the Hydra multi-object spectrographs, proper motions from the Tycho-2 catalogue, and the angular distance of the stars from cluster center. All these papers concern stars brighter than $V = 13$ mag and altogether list 48 stars for which the membership probability, P , is higher than 60 %.

We note, however, that Frinchaboy *et al.* (2008) perform separate computations of cluster membership from proper motions, P_{pm} , and from radial velocities, P_{rv} . Since for many stars these values differ significantly from each other, and because the final value of P computed by Frinchaboy *et al.* (2008) is a product of P_{pm} and P_{rv} , these authors find only one star for which $P > 90\%$, two, for which $P \simeq 50\%$, one, for which $P \simeq 20\%$, ten, for which $P \leq 10\%$, and 38, for which $P = 0$. These differences between P_{pm} and P_{rv} computed by Frinchaboy *et al.* (2008), differences between P_{pm} derived by Frinchaboy *et al.* (2008) and by Dias *et al.* (2002) from the same data (where P_{pm} given by Frinchaboy *et al.* (2008) is always lower than P_{pm} computed Dias *et al.* (2002)), and the very low number of stars classified by Frinchaboy *et al.* (2008) as cluster members is very unexpected. Because the origin of these discrepancies is not clear and their study is beyond the scope of this paper, in the following Sections we will take with care the probabilities computed by Frinchaboy *et al.* (2008) and refer only to the results obtained by Dias *et al.* (2002) and Kharchenko *et al.* (2004).

So far, the cluster has not been a subject of a variability search. The Hipparcos Catalogue (ESA 1997) classifies two stars, HIP 98610 and 98793, as unsolved variables (U), and the Tycho Catalogue (ESA 1997), five, HD 190044, 190465, 190657, 190966, and TYC2-3162-00893-1, as suspected variables (W).

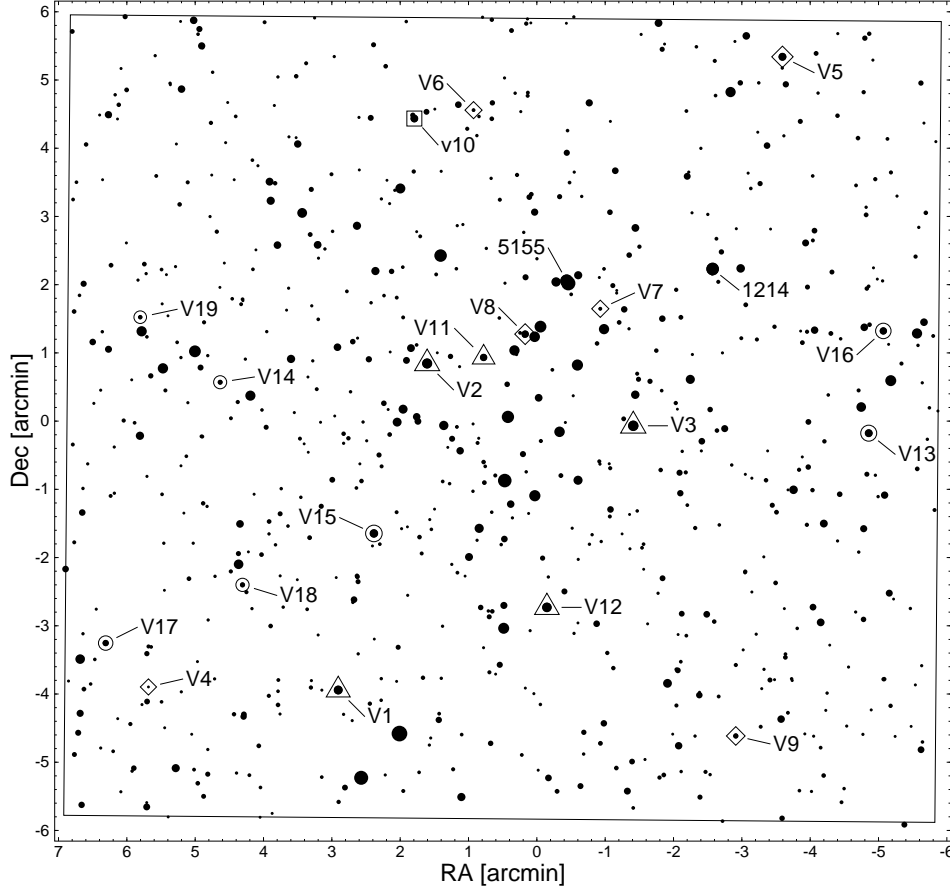


Fig. 1. The finding chart for the observed field in NGC 6866. Only stars brighter than 18 mag in V are shown. δ Sct and γ Dor stars are indicated with triangles, ellipsoidal and EW stars, with diamonds, the EA system, with a square, and irregular variables, with circles. The two blue-stragglers, NGC 6866-1214 and -5155, are indicated with their WEBDA numbers. The equatorial coordinates of point (0,0) are equal to $\alpha_{2000} = 20^{\text{h}}03^{\text{m}}55^{\text{s}}$, $\delta_{2000} = 44^{\circ}09'30''$.

The paper is organized as follows. In Sect. 2, we give an account of the observations and reductions. In Sect. 3, we compute the cluster membership of stars in the field of NGC 6866 and discuss the new variables. In Sect. 4, we construct the color-magnitude diagram for NGC 6866 and discover two blue-stragglers, the first such objects in the cluster. In Sect. 5 we discuss the issue of the age and metallicity of the open clusters in which γ Dor stars can exist. Sect. 6 contains a summary.

The numbering system of stars in NGC 6866 used in this paper is adopted from the WEBDA¹ database.

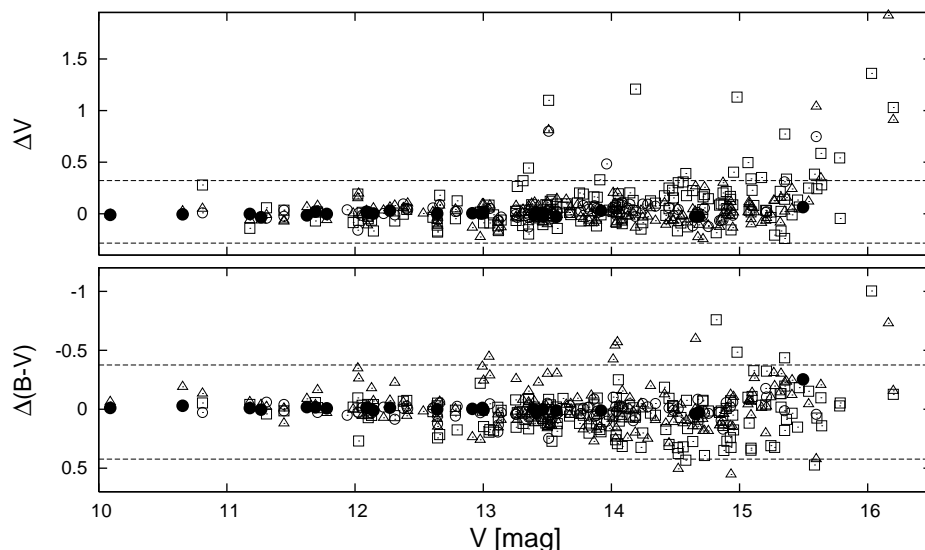


Fig. 2. The differences between the V magnitudes and $(B - V)$ colors from this paper and those from the photoelectric and photographic photometry of Hoag *et al.* (1961) (filled and open circles, respectively), the photographic photometry of Barkhatova & Zakharova (1970) (triangles), and the photographic photometry of Hidajat & Sutantyo (1972) (squares). The dashed lines indicate the limits adopted for the 3σ -clipping algorithm.

2. Observations and Reductions

Our observations were carried out at the Biłków Observatory of the Wrocław University on 14 nights between April 27 and July 21, 2007. We used a 60-cm Cassegrain telescope equipped with Andor DW432-BV back-illuminated CCD camera to observe one 12.8×11.7 arcmin² field in NGC 6866. We used BV and I_C filters of the Johnson-Kron-Cousins $UBV(RI)_C$ photometric system and collected 413 CCD frames in the B filter, 470, in V , and 469, in I_C . The exposure times were equal to 60 – 100 s, depending on the filter and the weather conditions.

In the pre-processing of the frames, the bias and dark frames were subtracted, the flat-field correction was applied, and the frames in the I_C filter were corrected for the fringing pattern. For all stars in the field the instrumental magnitudes were computed using the DAOPHOT profile-fitting software (Stetson 1987). The reductions were done as described by Jerzykiewicz *et al.* (1996).

In the I_C -band reference frame of the field, we identified 3798 stars for which we obtained meaningful photometry. The finding chart for the field we observed is shown in Fig. 1. To avoid crowding, we show only stars brighter than 18 mag in V .

We derived the differential photometry on a frame-to-frame basis, so that the instrumental photometry for each frame had to be shifted to a common magnitude scale defined by a selected reference frame as described by Kopacki *et al.* (2008). Then, the average v instrumental magnitudes and the $(b - v)$ colors-indices of all

¹<http://www.univie.ac.at/webda/webda.html>

Table 1

Mean differences between the V magnitudes and $(B - V)$ colors from this paper and from the literature.

	ΔV [mag]		N	N_{rej}	$\Delta(B - V)$ [mag]		N	N_{rej}
	mean	σ			mean	σ		
photoelectric:								
Hoag <i>et al.</i> (1961)	0.002	0.023	24	0	-0.011	0.054	24	0
photographic:								
Hoag <i>et al.</i> (1961)	0.018	0.065	81	3	0.015	0.065	84	0
Barkhatova and Zakharova (1970)	0.006	0.094	150	5	-0.001	0.148	147	8
Hidajat and Sutantyo (1972)	0.037	0.128	134	17	0.059	0.146	145	6

stars were transformed to the standard system using following equations

$$\begin{aligned}
 V - v &= -0.107(b - v) - 1.232, & \sigma &= 0.019 \text{ mag}, \\
 B - V &= +1.276(b - v) - 0.160, & \sigma &= 0.016 \text{ mag},
 \end{aligned}$$

that were obtained by the method of least squares from 24 bright stars in common with Hoag *et al.* (1961). Here, σ denotes standard deviation of the fit, V , the standard magnitude, and $(B - V)$, the standard color index.

In Fig. 2, we plot the differences between the V magnitudes and $(B - V)$ colors from this paper and those from Hoag *et al.* (1961), Barkhatova & Zakharova (1970), and Hidajat & Sutantyo (1972). In Table 1, we give the mean values of these differences which we calculated using a 3σ -clipping algorithm for rejecting outlying data points, the standard deviations of the sample, σ , the number of points used in calculations, N , and the number of the rejected data points, N_{rej} . The agreement between our measurements and those given in the literature is reasonably good. The V magnitudes and $(B - V)$ colors from this paper are given in Table 3, available in electronic form from the Acta Astronomica Archive.

T a b l e 2
Photometric data for variable stars in NGC 6866

Var	No	Type	α_{2000} [^h ^m ^s]	δ_{2000} [[°] ['] ^{''}]	V [mag]	$B - V$ [mag]	ΔB [mag]	ΔV [mag]	Δi_C [mag]	P [d]
V1	3213	δ Sct	20 04 11.19	44 05 33.5	12.976	0.319	0.009	0.008	0.008	0.066677
V2	2105	δ Sct	20 04 03.96	44 10 20.7	12.376	0.302	0.006	0.006	0.007	0.072465
V3	29	δ Sct	20 03 47.13	44 09 25.9	12.222	0.302	0.018	0.015	0.012	0.106414
							0.009	0.011	0.008	0.120744
							0.004	0.006	0.003	0.085202
V4	–	W UMa	20 04 26.66	44 05 36.2	–	–	–	–	0.601	0.262524
V5	1311	W UMa	20 03 34.93	44 14 50.4	13.524	0.443	0.030	0.047	0.055	0.321742
V6	–	W UMa	20 04 00.17	44 14 03.5	17.331	0.886	0.477	0.467	0.390	0.366528
V7	–	W UMa	20 03 49.82	44 11 08.8	17.196	0.862	0.384	0.341	0.308	0.41501
V8	39	Ell	20 03 55.96	44 10 46.5	13.868	0.430	0.047	0.029	0.024	0.6222
V9	133	Ell	20 03 38.79	44 04 53.1	15.543	0.773	0.213	0.193	0.169	0.43414
V10	–	EA	20 04 05.01	44 13 56.1	13.628	0.606	0.123	0.092	0.093	1.916
V11	21	γ Dor	20 03 59.34	44 10 26.0	13.919	0.431	0.100	0.069	0.043	0.8057
							0.036	0.036	0.018	0.9060
V12	4108	γ Dor	20 03 54.18	44 06 46.2	12.644	0.228	0.020	0.016	0.013	0.7077
V13	20	Irr	20 03 27.92	44 09 19.4	13.571	0.431	0.146	0.121	0.079	–
V14	–	Irr	20 04 20.84	44 10 04.2	15.796	1.180	0.279	0.176	0.113	–
V15	3110	Irr	20 04 08.29	44 07 51.2	13.080	2.043	0.133	0.097	0.047	–
V16	1220	Irr	20 03 26.72	44 10 49.3	13.751	2.120	0.223	0.083	0.035	–
V17	150	Irr	20 04 30.15	44 06 14.8	14.514	2.049	0.284	0.218	0.076	–
V18	–	Irr	20 04 19.00	44 07 06.0	15.570	2.108	0.770	0.395	0.148	–
V19	–	Irr	20 04 27.38	44 11 01.4	16.231	2.209	1.048	0.569	0.289	–

3. Variable Stars

For each star, the Fourier spectrum and an AoV periodogram (Schwarzenberg-Czerny 1989) were computed in the frequency range from 0 to 50 d^{-1} . These two methods were used because the former is useful for stars of which the brightness varies sinusoidally, while the latter, for eclipsing binaries. Then, we calculated the signal-to-noise ratio, S/N , of the highest peak in each spectrum and checked by eye the phase-diagrams corresponding to stars with $S/N \geq 4$ for the presence of a periodic variability or eclipses. In Fig. 3, we plot the S/N ratio of the highest peak in the frequency spectrum (in the figure we show only the $0\text{--}20 \text{ d}^{-1}$ part of the spectrum) against its frequency for all stars in the field.

We discovered 19 variable stars which we classified on the basis of the length of the detected period and the shape of the light-curve. We designated these stars V1 through V19. The stars are listed in Table 2, where we give their designation, the number from WEBDA, type of variability, equatorial coordinates, the mean brightness in V and the mean color-index ($B - V$) for all stars but the faintest V4 for which we do not compute the standard magnitudes, the range of variability in

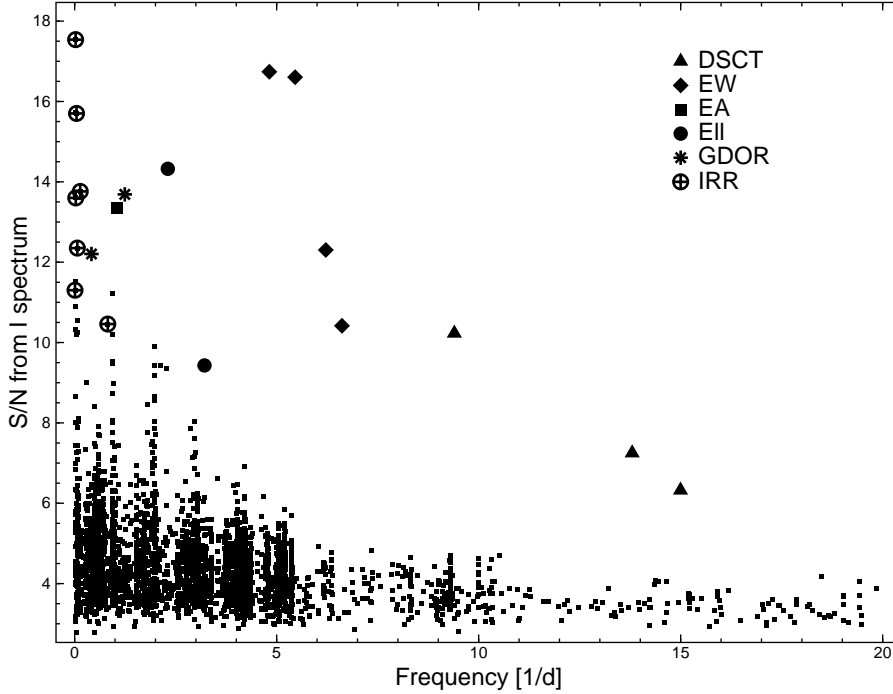


Fig. 3. The signal-to-noise ratio (S/N) of the highest peak in the frequency spectrum of the I-filter data for each star in the field we observed. Variable stars are indicated with the following symbols: δ Sct, triangles, γ Dor, asterisks, W UMa, diamonds, the EA system, a square, ellipsoidal variables, bullets, and irregular variables, encircled plus signs.

B , V and the instrumental i_C filter, and for the periodic variables, the period(s), P .

The variability of HIP 98793, NGC 6866-5, classified in the Hipparcos Catalogue as an unsolved variable, has not been confirmed in our data. We also do not confirm variability of this star in Hipparcos H_p magnitudes. The remaining suspected and unsolved variables listed in the Hipparcos and the Tycho Catalogues were not included in our field of view.

3.1. Cluster Membership

Only two of the 19 variables discovered in this paper have the cluster membership probability computed by Dias *et al.* (2002) or Kharchenko *et al.* (2004). Therefore, we used the proper motions from Röser *et al.* (2008) to compute the probability of membership in the cluster for stars from our field. First, we used stars that fall into the cluster area centered at $\alpha_{2000} = 20^{\text{h}}.065$, $\delta_{2000} = 44^{\circ}.16$ and limited by the radius of $0^{\circ}.14$ adopted from Kharchenko *et al.* (2005) to compute the mean proper motion of the cluster. The computations were done iteratively; we used a σ -clipping algorithm and rejected stars having the proper motion that differed from the mean proper motion by more than 3σ . The resulting value, $\mu_{\alpha} \cos \delta = -3.86 \pm 0.16$, $\mu_{\delta} = -4.63 \pm 0.17$ mas/yr (the uncertainty given here is the r.m.s. error), agrees well with the mean cluster proper motion computed by Dias

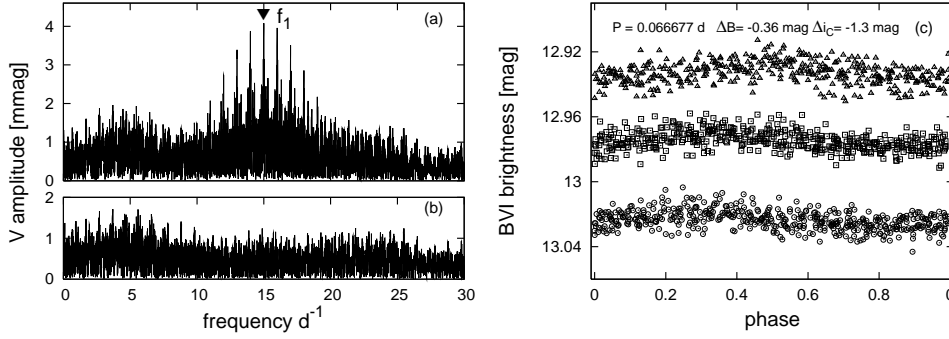


Fig. 4. Fourier spectra of the δ Sct star V1: (a) for original V-filter observations, (b) after prewhitening with frequency $f_1 = 14.9976$ d^{-1} (the ordinate scale is the same in both panels); (c) the light curves of V1 in B (triangles), V (squares) and the instrumental i_C filter (circles). ΔB and Δi_C are magnitude shifts applied to B and i_C data, respectively.

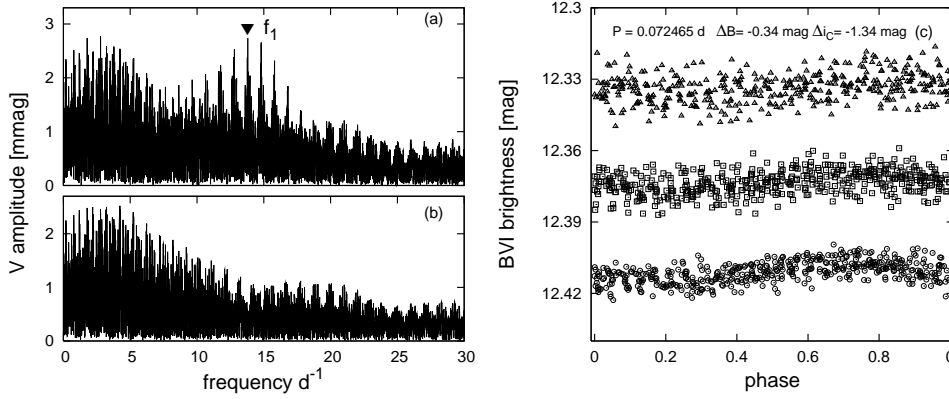


Fig. 5. The same as in Fig. 4 but for the δ Sct star V2. (a) The highest peak occurs at the frequency $f_1 = 13.7999$ d^{-1} (the ordinate scale is the same in both panels). (c) The light curves of V2 in B (triangles), V (squares) and the instrumental i_C filter (circles). ΔB and Δi_C are magnitude shifts applied to B and i_C data, respectively.

et al. (2002), $\mu_\alpha \cos \delta = -3.33 \pm 2.93$, $\mu_\delta = -5.03 \pm 2.93$ mas/yr, and Kharchenko *et al.* (2005), $\mu_\alpha \cos \delta = -3.48 \pm 0.40$, $\mu_\delta = -5.80 \pm 0.38$ mas/yr. The agreement with the values given by Frinchaboy *et al.* (2008), $\mu_\alpha \cos \delta = -5.5 \pm 1.2$, $\mu_\delta = -8.0 \pm 1.1$, is less satisfactory. We note that the uncertainties given by Dias *et al.* (2002) and Frinchaboy *et al.* (2008) are standard deviations while Kharchenko *et al.* (2005) give the r.m.s. errors.

Then, following Kharchenko *et al.* (2005), for each star for which the proper motion has been measured, we computed the cluster membership probability, P , as a measure of its deviation from the mean proper motion of the cluster, d . In the result, 23 stars with $d \leq \sigma$ (where σ is the standard deviation of the proper motions of the sample), i.e., $P > 60\%$, we classified as most probable cluster members, 20 stars with $1\sigma \leq d < 2\sigma$, i.e., $14\% \leq P \leq 60\%$, as possible members, 11 stars with $2\sigma \leq d < 3\sigma$, i.e., $1\% \leq P \leq 14\%$, as possible field stars, and 19 stars with $d < 3\sigma$,

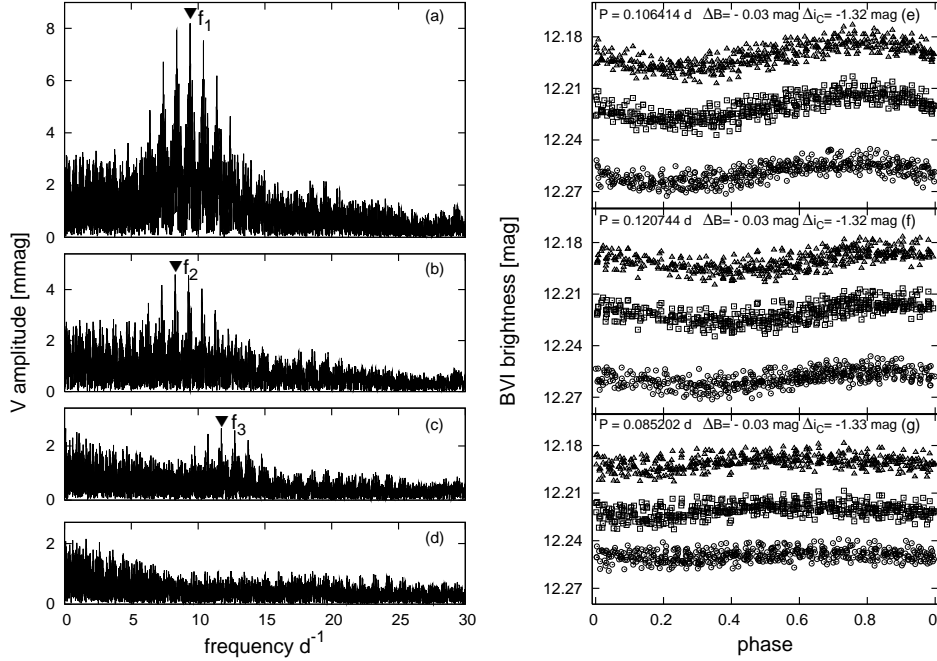


Fig. 6. Similar as in Fig. 4 but for the δ Sct star V3. The highest peaks occur at (a) $f_1 = 9.3973$ d^{-1} , (b) $f_2 = 8.2820$ d^{-1} and (c) $f_3 = 11.7368$ d^{-1} (the ordinate scale is the same in all panels.) (e) The light curves of V3 in B (triangles), V (squares) and the instrumental i_C filter (circles), prewhitened with the frequencies f_2 and f_3 , and phased with the frequency f_1 ; (f) – (g) the same as in (e) but for the frequencies f_2 and f_3 . ΔB and Δi_C are magnitude shifts applied to B and i_C data, respectively.

i.e., $P < 1\%$, as definite field stars. The cluster membership probability computed in this paper is listed in the last column of Table 3.

Our computations show that the δ Sct stars V1, V2 and V3, and the γ Dor star V12 belong to the cluster. The eclipsing binary, V10, and one of the irregular variables, V13, are definite field stars. For the other irregular variable V15, the cluster membership probability is 30 % so that it could be a cluster member. However, its location on the color-magnitude diagram far to the red of the main sequence (see Fig. 11) rules out that possibility.

3.2. δ Sct stars

We discovered two monoprotic δ Sct stars, V1 and V2, and one multiprotic δ Sct star, V3. V1 and V2 vary with the frequencies $f_1 = 14.9976$ and $f_1 = 13.7999$ d^{-1} , respectively. V3 shows three frequencies, $f_1 = 9.3973$, $f_2 = 8.2820$ and $f_3 = 11.7368$ d^{-1} . All these stars lie on the main sequence in the cluster's color-magnitude diagram (see Fig. 11) and for all the probability of cluster membership is high: 80 %, 71 % and 87 % for V3 computed by, respectively, Dias *et al.* (2002), Kharchenko *et al.* (2004) and in this paper, and 72 % and 94 % computed for V1 and V2 in this paper. Therefore, we consider all these stars to be

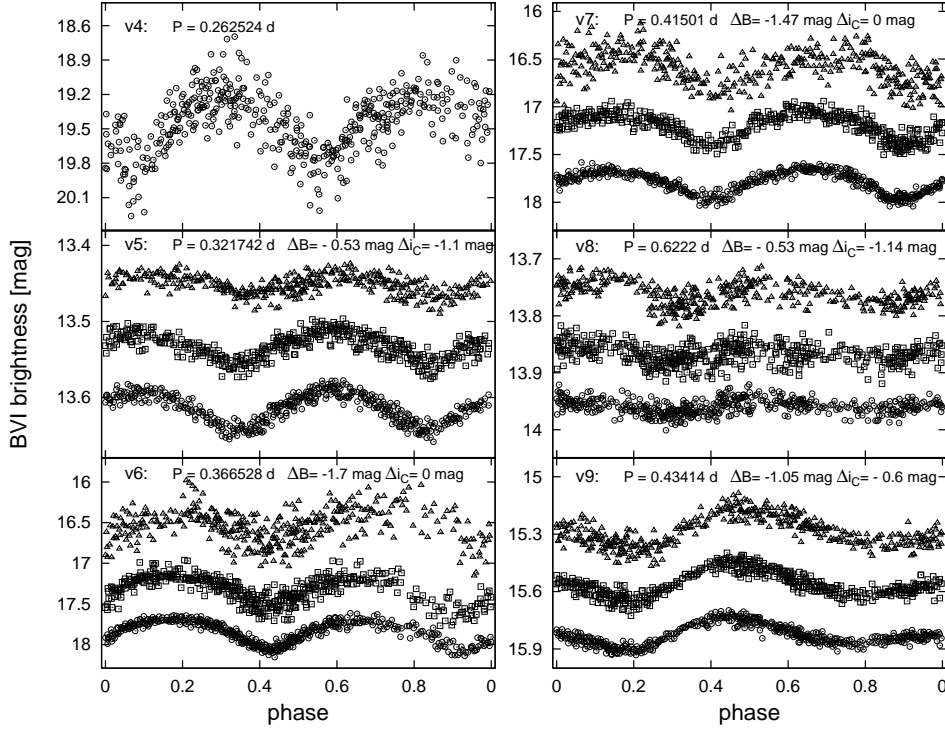


Fig. 7. The B (triangles), V (squares) and the instrumental i_C filter (circles) light curves of the W Ursae Majoris systems, V4, V5, V6 and V7, and the ellipsoidal stars, V8 and V9. ΔB and Δi_C are magnitude shifts applied to B and i_C data, respectively.

very probable members of NGC 6866.

We show the amplitude spectra of V1 and V2 in Figs. 4 and 5, respectively, and that of V3, in Fig. 6. The amplitude spectra of the residuals, plotted in Figs. 4b, 5b and 6d show only noise. In Figs. 4c, 5c and Fig. 6e-g, we plot the phase diagrams constructed from B , V and the instrumental i_C magnitudes. As can be seen from these figures, the stars show sinusoidal variations of the brightness in all filters.

3.3. WUMa and Ell stars

We discovered four WUMa type variables, V4, V5, V6 and V7, and two ellipsoidal variables, V8 and V9. We show their light curves in Fig. 7. For V4, we show only i_C -filter light curve because in the other filters the scatter masks the variation.

3.4. The eclipsing binary

Our time-series of V10 shows two minima which have the same shape of the ingress (the egress was observed only partially) and which we interpret as the same type of minimum. The BVi_C light-curves, phased with $P_{\text{orb}} = 1.916\text{d}$, are plotted in Fig. 8; we have checked that neither $0.5P_{\text{orb}}$ nor any other period fits the data. The observed minimum is flat. The brightness between eclipses is not constant.

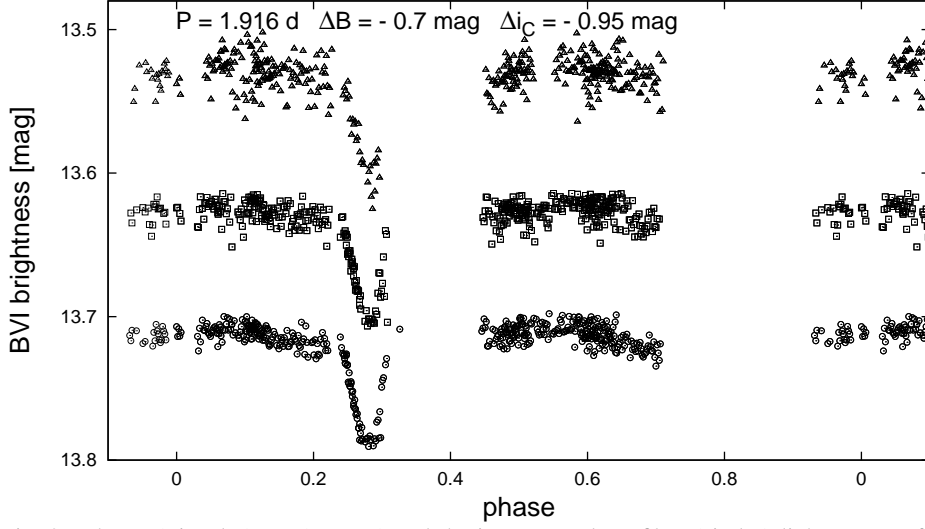


Fig. 8. The B (triangles), V (squares) and the instrumental i_C filter (circles) light curves of the eclipsing binary V10. ΔB and Δi_C are magnitude shifts applied to B and i_C data, respectively.

The proper motion of V10, $\mu_\alpha \cos \delta = -37.75 \pm 14.13$, $\mu_\delta = -54.14 \pm 14.3$ mas/yr (Röser *et al.* 2008), is around ten times higher than the mean proper motion of the cluster. The cluster membership probability of V10 computed in this paper is lower than 1%. Having reached the conclusion that V10 is a definite field star and keeping in mind its high proper motion, we suspected that V10 is a high-velocity metal-deficient Population II star.

Because our data do not allow deciding whether the primary or the secondary minimum has been observed, we calculated the range of magnitudes of the primary and the secondary component of V10 which give the observed magnitude at the quadrature, $V = 13.33$, $B = 13.76$ mag, and at the minimum, $V = 13.41$, $B = 13.86$ mag. Because the orbital inclination of the system has not been measured, in our calculations we adopted $i = 90^\circ$. The calculated magnitudes cover all the possible combinations of the magnitudes of the components, i.e., from the secondary component being so faint that it does not contribute to the mean brightness of the system outside eclipses to both components having the same brightness. The resulting B and V magnitudes of the primary, 1, and the secondary, 2, components fall into the following ranges: $m_{V,1} \in (13.33; 14.09)$, which corresponds to $m_{V,2} \in (+\infty; 14.09)$, and $m_{B,1} \in (13.76; 14.52)$, which corresponds to $m_{B,2} \in (+\infty; 14.52)$ mag.

Since we aimed at calculating the lower limit of the tangential velocity of V10, we assumed that the star is a not reddened metal-deficient dwarf, and that the brightness of its primary component is $V = 13.33$; any change in our assumptions, e.g., an increase of $E(B - V)$, higher magnitude of the primary component, or a higher metallicity (i.e., brighter absolute magnitude), would result in a higher tangential velocity of the star. We calculated the star's absolute magnitude, $M_V = 4.9$, from

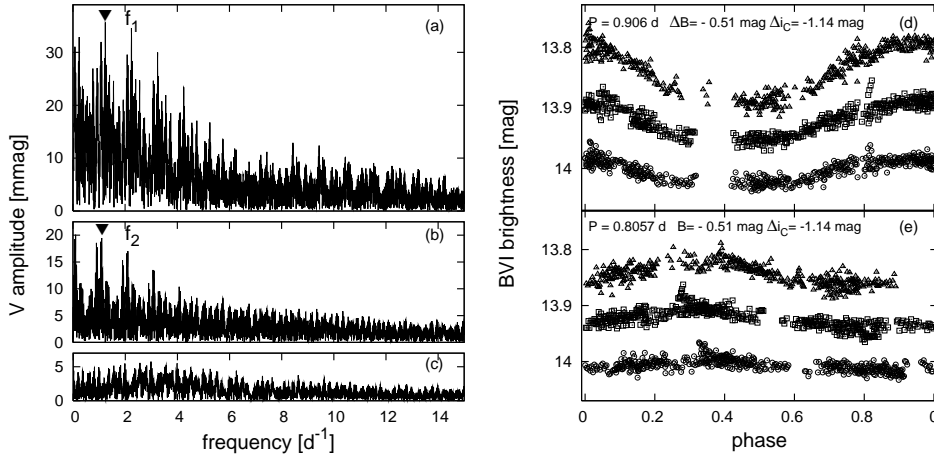


Fig. 9. Similar as in Fig. 4 but for the γ Dor star V11. The highest maximum occurs at (a) $f_1 = 1.2412 \text{ d}^{-1}$ and (b) $f_2 = 1.1038 \text{ d}^{-1}$ (the ordinate scale is the same in all panels.) (d)–(e) The B (triangles), V (squares) and the instrumental i_C filter (circles) light curves of V11. ΔB and Δi_C are magnitude shifts applied to B and i_C data, respectively.

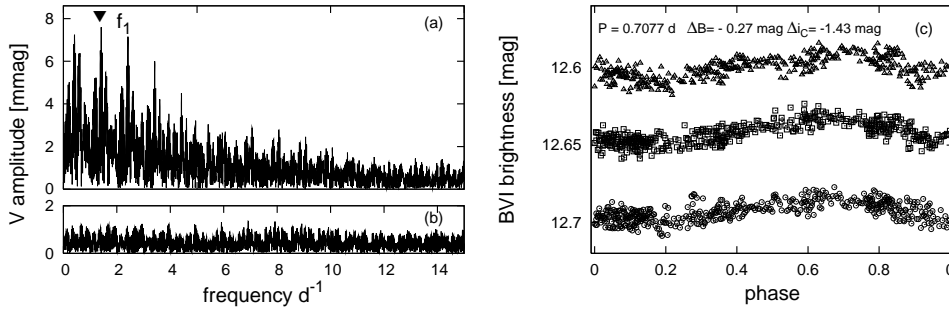


Fig. 10. The same as in Fig. 4 but for the γ Dor candidate V12. (a) The highest maximum occurs at the frequency $f_1 = 1.4130 \text{ d}^{-1}$ (the ordinate scale is the same in both panels.) (c) The B (triangles), V (squares) and the instrumental i_C filter (circles) light curves of V11. ΔB and Δi_C are magnitude shifts applied to B and i_C data, respectively.

$M_V - (B - V)$ relation of Karataş & Schuster (2006) for metal-poor stars. Then, we calculated the distance to the star, $r = 489 \text{ pc}$, and its tangential velocity, 152 km/s . Since the calculated value is higher than 100 km/s , which is the lower limit of tangential velocity of high-velocity stars (see, e.g., Lee (1984)), we classify V10 as a new high-velocity star in the field of NGC 6866.

3.5. γ Dor stars

Two stars in NGC 6866 show variability on time-scale of a day; V11, which shows two frequencies, $f_1 = 1.2412 \text{ d}^{-1}$ and $f_2 = 1.1038 \text{ d}^{-1}$, and V12, which shows one frequency, $f_1 = 1.4130 \text{ d}^{-1}$. For both stars, the amplitudes are the highest in the B filter and the smallest, in i_C , and the light-curves are sinusoidal. The amplitude spectra and phase diagrams for V11 and V12 are shown in Figs. 9 and 10.

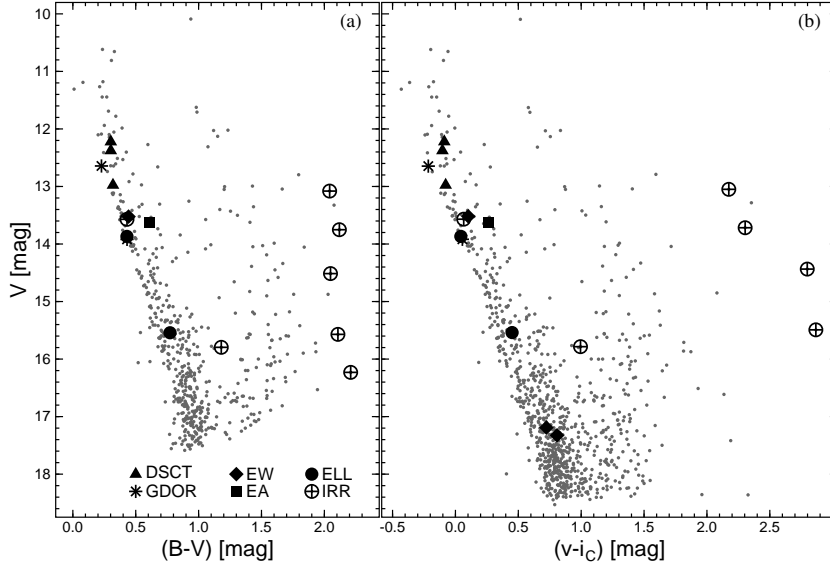


Fig. 11. (a) The standard $(B-V)$ vs. V and (b) the instrumental $(v-i_C)$ vs. V color – magnitude diagrams for NGC 6866. δ Sct stars are indicated with triangles, γ Dor, with asterisks, W UMa, with diamonds, the eclipsing binary, with a square, ellipsoidal variables, with bullets, and irregular variables, with encircled plus signs. Panel *b* does not include V19 for which $(v-i_C) = 4.48$ mag.

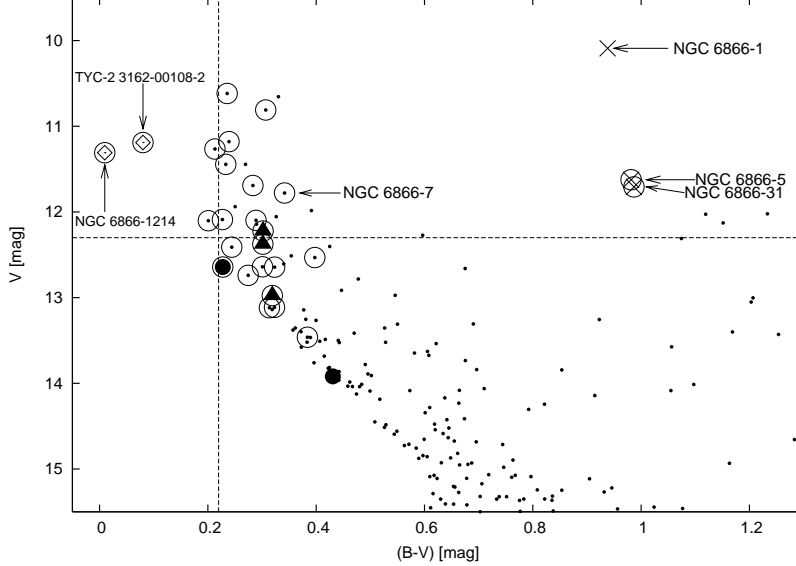


Fig. 12. A zoom of Fig. 11a. Circles indicate stars for which the membership probability is higher than 60 %. Blue-stragglers are indicated with open diamonds, red giants, with crosses. δ Sct stars are indicated with triangles, γ Dor stars, with bullets; the remaining variables are not included. The intersection of the dashed lines indicates the turn-off point of the cluster, i.e., m_v and $(B-V)$ of an A3V star in a distance of 1200 pc and reddened with $E(B-V) = 0.14$ mag. NGC 6866-7 is a rejected blue-straggler candidate.

The probability of membership of V12 in NGC 6866 is 97% or 66 % according to Kharchenko *et al.* (2004) and this paper, respectively. The cluster membership of V11 has not been computed. However, as both stars fall on the cluster main sequence, we consider both V11 and V12 to be probable cluster members.

Having discovered the multiperiodic variability of V11, and taking into account the length of the detected periods, we classify the star as a γ Dor – type variable. The other star, V12, we classify as a γ Dor suspect on the basis of the length of the detected period and the increase of the amplitude of its variability towards the shorter wavelengths.

In Sect. 5, we discuss the phenomenon of the occurrence of γ Dor stars in open clusters in more detail.

3.6. Irregular variables

The irregular variables V13, V14, V15, V16, V17, V18 and V19 form the largest group of variable stars discovered in the field of NGC 6866. We computed the probability of membership in the cluster for V13 and V15. V13, which falls on the cluster main sequence (see Fig. 11), turned out to be a definite field star, and V15, which might be a probable cluster member, is excluded as such because of its position far to the red of the cluster main sequence. Therefore, we consider all the irregular variables to be non-members.

4. The Color – Magnitude Diagram

In Fig. 11a and b, we show V vs. $(B - V)$ and V vs. the instrumental $(v - i_C)$ color-magnitude diagrams for stars in the field of NGC 6866 for which we have reliable photometry. The intersection of the dashed lines in Fig. 12b indicates the turn-off point of the cluster, A3, estimated by Johnson *et al.* (1961).

As can be seen from these figures, most stars fall on the main sequence; the red giant clump is not visible. Indeed, in NGC 6866 there are only four red giants listed by Mermilliod *et al.* 2008: NGC 6866-1, 5, 26 and 31. (We note, however, that NGC 6866-1 has been classified by Sowell (1987) to G5V.) We observed three of these stars; NGC 6866-26 was outside of our field of view.

4.1. Blue-stragglers

NGC 6866 is at the age at which, according to De Marchi *et al.* (2006), it should host one or two blue-stragglers (see Table 1 in De Marchi *et al.* 2006). Unfortunately, the only blue-straggler suspect, NGC 6866-7 (Hoag *et al.* 1961), has been rejected by Ahumada & Lapasset (2007). In the color-magnitude diagram in Fig. 12, this star falls to the red of the main sequence and below the turn-off point and therefore we also reject the possibility that NGC 6866-7 is a blue-straggler.

In Fig. 12, there are, however, two other stars, NGC 6866-1214 and TYC-23162-00108-2 (which is the north-east faint component of NGC 6866-5155), that

Table 4

The list of Galactic open clusters which host candidates for γ Dor stars.

cluster	$N_{\gamma\text{Dor}}$	log age	[Fe/H]	cluster	$N_{\gamma\text{Dor}}$	log age	[Fe/H]
NGC 581	2 [1] (1 nm)	7.1 [2] 7.3 [2]	-0.85 [3] —	NGC 6633	2 [61]	8.6 [25] 8.8 [38]	-0.30 [22] +0.06 [39]
NGC 659	3 [4]	7.3 [5] 7.6 [6]	— —	NGC 6705	2 [40,41] (1 nm)	8.3 [12] 8.4 [42]	+0.07 [9] +0.21 [43]
NGC 1039	2 [7]	8.3 [8] 8.4 [8]	-0.29 [9] +0.07 [10]	NGC 6755	4 [44] (2 nm)	7.7 [12] 8.2 [3]	-0.03 [3] +0.14 [15]
NGC 1245	4 [11]	8.7 [12] 9.0 [13]	-0.05 [14] +0.10 [15]	NGC 6866	2 [45]	8.4 [46] 8.8 [47]	+0.10 [47] —
NGC 1817	1 [16] (1 nm?)	8.9 [17] 9.1 [18]	-0.42 [19] +0.18 [15]	NGC 7086	1 [48]	8.0 [48] 8.1 [12]	— —
NGC 2099	2 [20] (1 nm?)	8.2 [21] 8.3 [21]	-0.07 [22] +0.18 [23]	NGC 7762	2 [49,50]	8.4 [12] 9.4 [49]	— —
NGC 2301	2 [24]	8.2 [25] 8.5 [24]	+0.01 [23] +0.06 [25]	Pleiades	2 [37]	7.9 [31] 8.1 [42]	-0.03 [34] +0.11 [12]
NGC 2506	15 [26]	9.1 [12] 9.3 [27]	-0.57 [28] -0.20 [29]	α Per	2 [52]	7.7 [53] 8.0 [54]	-0.05 [51] +0.07 [9]
NGC 2516	8 [30]	8.1 [31] 8.2 [32]	-0.42 [15] +0.02 [15]	Coma Ber	1 [55]	8.5 [56] 8.7 [38]	-0.05 [56] -0.03 [58]
NGC 2539	1 [31] (1 nm)	8.8 [33] 8.9 [33]	-0.20 [33] +0.16 [16]	Praesepe	1 [52]	8.8 [59] 8.9 [52]	+0.08 [22] +0.27 [60]
NGC 6231	3 [34]	6.5 [35] 6.7 [35]	-0.13 [36] +0.26 [3]				

[1] Wyrzykowski *et al.* 2002, [2] Sanner *et al.* 1999, [3] Tadross 2003, [4] Pietrzyński *et al.* 2001, [5] Phelps and Janes 1994, [6] Lata *et al.* 2002, [7] Krisciunas and Crowe 1996, [8] Jones and Prosser 1996, [9] Cameron 1985, [10] Schuler *et al.* 2003, [11] Pepper and Burke 2006, [12] WEBDA, [13] Subramaniam 2003, [14] Burke *et al.* 2003, [15] Gratton 2000, [16] Arentoft *et al.* 2005, [17] Harris and Harris 1977, [18] Balaguer-Núñez *et al.* 2004, [19] Friel and Janes 1993, [20] Hartman *et al.* 2008, [21] Kalirai *et al.* 2001, [22] Janes 1979, [23] Piatti *et al.* 1995, [24] Kim *et al.* 2001b, [25] Chen *et al.* 2003, [26] Arentoft *et al.* 2007, [27] Kim *et al.* 2001a, [28] Friel and Janes 1993, [29] Carretta *et al.* 2004, [30] Zerbi *et al.* 1998, [31] Choo *et al.* 2003, [32] Bonatto and Bica 2005, [33] Clariá and Lapasset 1986, [34] Arentoft *et al.* 2001, [35] Baume *et al.* 1999, [36] Kilian *et al.* 1994, [37] Martín and Rodríguez 2002a, [38] Lyngå 1987, [39] Santos *et al.* 2009, [40] Koo *et al.* 2007, [41] Hargis *et al.* 2005, [42] Magrini *et al.* 2009, [43] Thøgersen *et al.* 1993, [44] Ciechanowska *et al.* 2007, [45] this paper, [46] Lindoff 1968, [47] Loktin *et al.* 1994, [48] Rosvick and Robb 2006, [49] Maciejewski *et al.* 2008, [50] Szabo 1999, [51] Boesgaard and Friel 1990, [52] Martín and Rodríguez 2002b, [53] Makarov 2006, [54] Stauffer *et al.* 1999, [55] Martín 2003, [56] Sandage 1958, [57] Friel and Boesgaard 1992, [58] Cayrel *et al.* 1988, [59] Bouvier *et al.* 2001, [60] Pace *et al.* 2008, [61] Martín and Rodríguez 2001.

fulfill all the requirements of bona fide blue-stragglers specified by Ahumada & Lapasset (2007): their cluster membership probability is high: 79 %, 52 % or 90 % for NGC 6866-1214, and 74 %, 62 % or 54 % for TYC-2 3162-00108-2, as computed by Dias *et al.* (2002), Kharchenko *et al.* (2004) and in this paper, respectively, (although Frinchaboy *et al.* (2008) give $P = 0$ % for both stars), both fall into the area of the color-magnitude diagram where blue-stragglers are expected (cf. Fig. 12 of this paper and Figs. 1 and 2 of Ahumada & Lapasset 2007), both are fainter than 2.5 mag limit above the cluster turnoff point, and fall close to the center of the cluster.

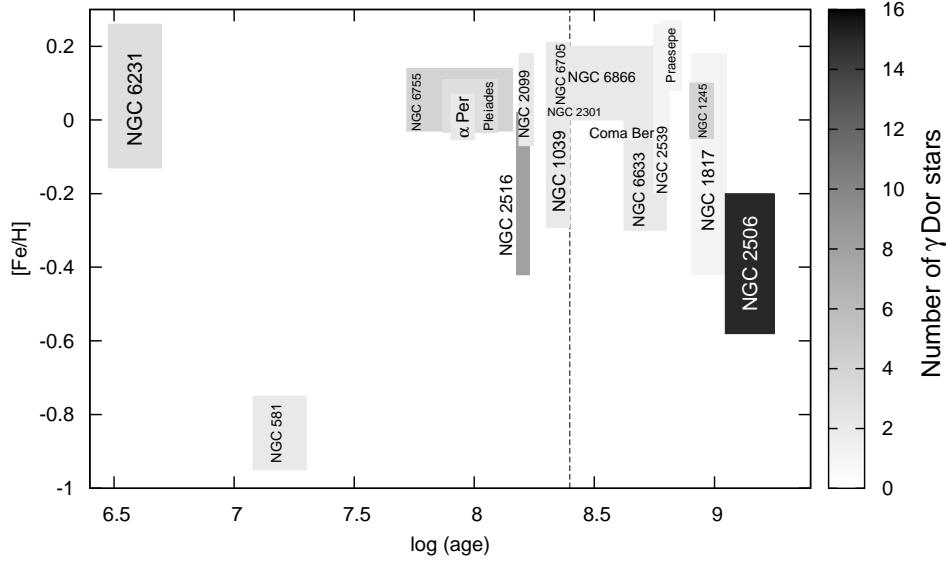


Fig. 13. The number of γ Dor stars in open clusters coded with shades of gray. The size of each box represents the uncertainty of determination of the age and $[\text{Fe}/\text{H}]$ of the cluster. The vertical line at 250 Myr indicates a suspected upper limit of the age of an open cluster that can host γ Dor stars (see Krisciunas and Patten 1999).

Therefore, we classify NGC 6866-1214 and TYC-2 3162-00108-2 as the first blue-stragglers discovered in the field of NGC 6866.

5. Discussion

Hosting one γ Dor star and one γ Dor candidate, NGC 6866 joins the group of 20 galactic open clusters in which a total of 62 candidates for γ Dor type pulsators have been discovered. We list these clusters in Table 4, where we give the number of γ Dor candidates in the cluster (including the non-member γ Dor stars, nm, the number of which, if known, is given below in brackets), and the range of the determinations of the age and metallicity of the cluster. The numbers in square brackets refer to the papers listed at the bottom of the Table. In Fig. 13, we use the shades of gray to plot the number of γ Dor candidates in the $\log(\text{age}) - [\text{Fe}/\text{H}]$ plane. Below we discuss the properties of clusters that host γ Dor candidates.

First, we see that, as already noticed by Eyer *et al.* (2002), there is no relationship between the age of an open cluster and the incidence of γ Dor stars. The phenomenon of γ Dor pulsators can occur in clusters as young as NGC 6231 (3 Myr, Baume *et al.* 1999) and as old as NGC 2506 (1.8 Gyr, Kim *et al.* 2001a). An upper limit of the age of γ Dor – hosting open clusters, equal to 250 Myr according to Krisciunas & Patten (1999), does not exist, because around 40 % of the clusters is older than that.

Second, γ Dor stars seem to have little preference concerning the metallicity

of the cluster; $[\text{Fe}/\text{H}]$ of all but one cluster from Table 4 falls into the range from -0.2 to $+0.2$ dex to within its error bars. Moreover, candidates for γ Dor stars occur in clusters as metal-rich as Praesepe, $[\text{Fe}/\text{H}] = +0.27$, and as metal-poor as NGC 581, $[\text{Fe}/\text{H}] = -0.85$. We note also that although NGC 2506 and NGC 2516, i.e., the clusters in which the number of γ Dor candidates is the highest, are the most metal-deficient ones, it needs to be confirmed how many of their γ Dor candidates really pulsate and how many are cluster members.

The membership of γ Dor candidates in a cluster is another issue that has not been studied sufficiently. For eight clusters only, NGC 581, 1817, 2301, 2516, 6633, 6705, 6866, and 7086, the probability of cluster membership has been derived from the proper motions. For four clusters, NGC 1817, 2516, 6705, and 6866, both proper motions and color-magnitude diagrams were used, leading to different results for some stars (see Arentoft *et al.* 2005). For NGC 659, 2099, 2506, 2539, 6231, 6755, 7762, and the Pleiades, the cluster membership was determined only from the color-magnitude diagrams, for NGC 1245, from the background star counts (Burke *et al.* 2004), and for NGC 1039, α Per, Praesepe, and Coma Ber, the probability of membership has not been computed.

The last but not least issue is the mechanism of the observed variability of these stars. All the 22 monophasic γ Dor candidates detected in the open clusters need to be confirmed as pulsators while the multiphasic ones require further study to check which of the detected frequencies are due to pulsations and which to, e.g., Ell or $\alpha^2\text{CVn}$ type of variability.

Summarizing, we conclude that at the present stage it is not possible to find statistically significant relation between the age or metallicity of an open cluster and the number of γ Dor stars therein.

Acknowledgements. This work was supported by MNiSW grant N203 014 31/2650 and the University of Wrocław grant No 2646/W/IA/06. We acknowledge A. Pigulski and G. Michalska for taking some observations used in this paper. We also thank Prof. M. Jerzykiewicz for his kind advice which helped us improve our paper. The authors made use of the WEBDA database, operated at the Institute for Astronomy of the University of Vienna, and of the NASA's Astrophysics Data System.

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